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Welded Columns and Flame-Cut Plates

RESIDUAL STRESSES IN WELDED SHAPES
OF FLAME-CUT PLATES IN ASTM A572(50) STEEL

by

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and

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This work has been carried out as a part of an investigation sponsored by the American Iron and Steel Institute.

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June 1969

Fritz Engineering Laboratory Report No. 321.2

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ABSTRACT

This report describes the result obtained from an investigation into the magnitude and distribution of residual stress in H-shapes welded from flame-cut plates, as well as in the component loose plates. Residual stress measurements were made in two welded H-shapes, 12H79 and 14H202, made of ASTM A572(Grade 50) steel. The method of sectioning was used for the determination of residual stress distribution.

The results show that very high tensile residual stresses exist at the portion near the flange tips and at the web-to-flange junction parts. They are caused by flame-cutting and by welding. These tensile stresses are balanced by almost uniformly distributed compressive stresses in the remaining parts of the cross section.

A comparison of the results obtained on the members of A572(50) steel and previous results

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for similar plates and shapes of A36 steel indicates that the yield stress of the material has practically no effect on the magnitude and distribution of residual stresses.

1. INTRODUCTION

1.1 Purpose and Scope

The purpose of the overall investigation is to study the strength and behavior of steel columns welded from flame-cut plates. This phase was concerned with the magnitude and the distribution of residual stress in medium size welded H-shapes manufactured from flame-cut plates of ASTM A572 (Grade 50) steel.⁽¹⁾

Two different column shapes are investigated in this report, a 12H79 and a 14H202 shape*. The dimensions of these shapes are shown in Fig. 1. Results of residual stress measurements on these two shapes are presented and a comparison is made with the results obtained on the same shapes of A36 steel.⁽²⁾

Welded flame-cut shapes are expected to have a favorable distribution of residual stress for column strength, because of the high input during the flame-cutting process, which introduces

*"H" designates a welded H-shape, while "WF" is for a rolled wide-flange shape.

tensile residual stresses at the plate edges. These tensile residual stresses will remain after welding the plates into a shape, although the magnitude of the stresses may be somewhat lowered. The distribution is "favorable", since the tensile stress at the flange tip improve column strength.

1.2 Manufacture and Fabrication

During the manufacturing and fabrication processes for welding the shapes, the material is subjected to various heat inputs which will produce residual stresses in the cross section. The first heat input that affects the residual stress distribution is the rolling of plates. The temperature of the plate during rolling is about 2,400°F. The rolling introduces compressive residual stresses at the plate edges and tensile residual stresses at the center of the plate. The second high heat input is during the flame-cutting of plates, when heat is applied locally to the plate. The flame-cutting creates tensile residual stress along the plate edges, being balanced by compressive stresses elsewhere in the plate; these stresses are superimposed on those due to rolling. Finally, the welding of the flame-cut plates to form the shape

causes additional residual stresses. Very high tensile stresses are formed in the weld region and compressive stresses elsewhere. The magnitude of tensile residual stress due to welding reaches the yield stress of the material, as compared to the stresses in rolled medium size wide-flange shapes which are much smaller than the yield stress of the parent material.

1.3 Background Information on Residual Stress Studies

Previous studies into residual stress distributions in welded flame-cut wide-flange shapes show that these shapes have high tensile residual stresses at flange tips and in the vicinity of welds.^(2,3) The pattern of residual stress distribution is found to be less dependent on the material, when 36 ksi steel is compared with 50 ksi steel. The major factor that influences the residual stress pattern is the geometry of the cross section; thickness of flange and web plates, width of flange, and the depth of shape.⁽⁴⁾

Residual stresses in two welded shapes of A36 steel were investigated in the earlier phase of the research program.⁽²⁾ The two shapes studied were

12H79 and 14H202 which were fabricated from flame-cut plates. The results obtained on A36 steel is included in this report for a comparison with the one on A572(50) steel.

2. DESCRIPTION OF TESTS

Two types of experiments were carried out; tension specimen tests to determine the mechanical properties of the material used, and residual stress measurements to find the magnitude and the distribution of residual stresses in flame-cut plates and H-shapes fabricated from these plates.

2.1 Tension Specimen Tests

Tension test specimens were cut both from shapes and their component loose plates for the 14H202 shape, and only from the shape itself for the 12H79 shape. The location of these specimens in the cross section are shown in Fig. 2 with the dimensions of these specimens, and one in the column shapes are given in Fig. 3. Testing machines used for the tension specimen tests are a mechanical testing machine of 120 kip capacity for the 12H79 specimens, and a hydraulic type machine of 300 kip capacity for the 14H202 specimens. The results include obtained complete stress-strain curves drawn by an automatic recorder. The data were evaluated for static yield

stress (σ_{ys}), strain at the onset of strain-hardening (ϵ_{st}), strain-hardening modulus (E_{st}), ultimate tensile stress (σ_u), percent elongation in 8 inch gage length, and percent reduction of area.

The number of tension specimens tested from the various members is shown in Table 1.

2.2 Residual Stress Measurements

For the determination of the magnitude and the distribution of residual stress, the method of sectioning^(5,6) was adopted using a Whittemore mechanical strain gage with a 10 inch gage length, which is shown in Fig. 4 together with the mild steel bar for the temperature compensation.

The number of specimens used for residual stress measurement is given in Table 1. The location of the specimens in the fabricated column members are shown in Fig. 3. The distance from the end of the member to these sections was chosen to be at least one and a half times the largest linear dimension of the cross section. Thus, the stress existing in a long member was contained in the test specimen.⁽⁵⁾

The method of sectioning requires at least two measurements of each gage length; once before sectioning, and then after sectioning the specimen into strips. Furthermore, in this study, one additional step was included, which is called "partial sectioning". This is an intermediate step before complete sectioning as shown in Fig. 5. A smaller number of longitudinal cuttings are made for the partial sectioning (Fig. 5b) than for complete sectioning, which is the final step as shown in Fig. 5c. The purpose of this intermediate step is to have an approximate idea of the residual stress distribution and also to see if the number of sections can be reduced in future tests.

Thus, referring to Fig. 5, the steps of residual stress measurements are as follows:

1. Preparation of gage holes and layout of sectioning lines on the specimen.
2. Initial readings.
3. Transverse cutting. (Fig. 5a)
4. Partial sectioning. (Fig. 5b)
5. Readings after partial sectioning.
6. Complete sectioning. (Fig. 5c)

7. Final readings.

To evaluate residual stress from Whittemore gage readings, the following formula was used.

$$\sigma_{ri} = \frac{E}{L} [(\bar{B}_i - \overline{\text{Ref.}\bar{B}_i}) - (\bar{A}_i - \overline{\text{Ref.}\bar{A}_i})]$$

where,

σ_{ri} = residual stress of the strip i,

E = modulus of elasticity,

L = gage length,

\bar{B}_i = average of the initial readings on the strip i,

$\overline{\text{Ref.}\bar{B}_i}$ = average of reference bar readings for the strip i before sectioning,

\bar{A}_i = average reading on the strip i after sectioning,

$\overline{\text{Ref.}\bar{A}_i}$ = average of reference bar readings for the strip i after sectioning.

Details of the sectioning are shown in Figs. 6 and 7 for the 12H79 and 14H202 shapes, respectively. The location of cuts for the partial sectioning is also indicated in Fig. 7 for the shape

14H202. For the component loose plates of the 14H202 shape, Fig. 8 shows details of the partial and complete sectioning of web (Fig. 8a) and flange (Fig. 8b) loose plates.

3. TEST RESULTS

3.1 Tension Specimen Test Results

The results obtained from tension specimen tests are summarized in Table 2. The data include static yield stress (σ_{st}), ultimate tensile stress (σ_u), modulus of elasticity (E), strain-hardening modulus (E_{st}), strain at the onset of strain-hardening (ϵ_{st}), percent elongation in 8 inch gage length, and percent reduction of area. Mechanical properties of the material as specified by the ASTM Standard (Designation A572-66)⁽¹⁾ are yield stress, tensile strength, and elongation in 8 inch gage length. The properties of the material used satisfied the ASTM requirements for A572 (Grade 50) steel.

As can be seen from the values of percent elongation in an 8 inch gage length and of percent reduction of area as well as from the specification, this low alloy high strength steel has a fairly good ductility.

Average stress-strain curves using the average values of these data (E , σ_{ys} , ϵ_{st} , and E_{st}) are shown in Fig. 9 for both shapes. The curve for the 14H202 shape shows a more gradual offset from elastic range, a lower static yield stress, and an earlier onset of strain-hardening than the one for the 12H79 shape. This could be due to the geometric effect (see Fig. 2 for the dimensions of tension test specimens) and due to small residual stresses left in the larger specimens cut from the 14H202 shape and from its component plates.

3.2 Residual Stresses in As-Manufactured Plates

Residual stress measurements were carried out on three loose plates taken from the same parent plate as the component plates of the 14H202 shape; one web plate (4D, 12 5/8" x 15/16") and two flange plates (4E and 4F, 15 3/4" x 1 1/2").

Residual stress distributions obtained on these plates are shown in Figs. 10, 11, and 12. Figure 10a shows the distribution of residual stress obtained on the web plate (4D) after partial sectioning and Fig. 10b the one after complete

sectioning. For the flange loose plates (4E and 4F), similar diagrams are given in Figs. 11 and 12.

Comparing the diagrams corresponding to partial sectioning and complete sectioning on these three loose plates, it is noted that the partial sectioning procedure gives a good indication of the actual residual stress distribution, although only two cuts were made on each plate. Since the number of cuts and the number of measurements necessary for the partial sectioning is far less than what is required for the complete sectioning procedure, this suggests a simpler method to obtain an estimate of the residual stresses by taking the step in between these two steps.

Considerably high tensile residual stress exists at the flame-cut edges of the plates. These tensile stresses are balanced by an almost uniform compressive residual stress elsewhere in the plate. Some irregularity is observed in the distribution of residual stress at the edges of the flange plate 4E after complete sectioning as is seen in Fig. 11b. For this plate, there appears to be a steep stress gradient across the plate thickness at the edges.

3.3 Residual Stresses in Welded H-Shapes

Residual stress measurements were carried out also on welded H-shapes of two different sizes, 12H79 and 14H202.

Residual stress distributions obtained on three identical sections of 12H79 shape are shown in Figs. 13a, b, and c. As is seen in these diagrams, there exist very high tensile residual stresses in the welds and also high tensile residual stresses at the flange tips which are due to the flame-cutting of plates. Compressive residual stresses are rather uniformly distributed elsewhere in the section to allow equilibrium of the cross section. Although there is some irregularity in the upper right flange in Fig. 13b, the pattern of residual stress distribution is basically the same in all three sections. Since these three sections were cut originally from one long member, it can be noted that residual stress distribution is constant along the length of the member.

For the shape 14H202 of A572(50) steel, residual stress distributions are shown in Figs. 14a

and b. These two sections were cut from the same material. The tendency of the distribution is more or less similar to the one in 12H79 shape. The main difference in the distribution of residual stresses in these two shapes is that the highest compressive residual stress is on the outside surface of the flange at the web-to-flange junction in 14H202 shape, while in 12H79 shape this is in tension.

4. DISCUSSION OF RESULTS

Summarizing the residual stress distribution in the component loose plates of the 14H202 shape of A572(50) steel, Fig. 15 shows the average distribution in the loose web plate (4D). For the diagram, average values are obtained from the stresses on both surfaces of the plate. The average tensile residual stress at the flame-cut edge is 43 ksi and the compressive residual stress in the mid-portion of the plate is approximately 4 ksi. These values correspond to $0.8 \sigma_{ys}$ and $0.07 \sigma_{ys}$, respectively, where σ_{ys} is the static yield stress obtained from tension tests and is equal to 55.0 ksi for the web loose plate.

For the flange loose plates (4E and 4F), the similar diagram is shown in Fig. 16. The average tensile residual stress at the plate edge is 25 ksi and the compressive stress in mid-portion is approximately 3 ksi. They are $0.5 \sigma_{ys}$ and $0.06 \sigma_{ys}$, respectively, where the static yield stress obtained

from tension specimen tests is equal to 53.0 ksi for the flange loose plates.

As for the residual stress distribution in the welded H-shapes built-up from flame-cut plates, Fig. 17 shows the average distribution in the 12H79 shape of A572(50) steel together with the one in A36 steel. Average stresses are calculated by taking one half of a flange and one half of a web as units. That is, each point in the flange represents the average of 24 stresses, and the one in the web represents 12 stresses measured. The average tensile stress for the A572(50) steel shape is 15 ksi at the flange tip and 43 ksi at the weld, which correspond to $0.3 \sigma_{ys}$ and $0.8 \sigma_{ys}$, respectively, the average static yield stress (σ_{ys}) being 55.8 ksi. The residual stress in the mid-portion of the flange is approximately 15 ksi in compression, and the one in mid-portion of the web is about 4 ksi in tension, that is, $0.3 \sigma_{ys}$ and $0.06 \sigma_{ys}$, respectively.

As may be seen in Fig. 17, the residual stress distribution is very similar in both types of steel and so is the magnitude of residual stresses. This implies that the type of steel does not greatly affect the magnitude and the distribution of residual stress.

For the 14H202 shape, the average residual stress distributions in the members of both A572(50) and A36 steels are shown in Fig. 18. Again the average stresses are computed on the basis of one half flange and one half web.

The residual stress distribution is very similar to the one in 12H79 shape, and the pattern is similar for both A572(50) and A36 steels. For the shape of A572(50) steel, the average tensile residual stresses are 20 ksi at the flange tip, and 27 ksi at the web-to-flange junction part. Since the average static yield stress determined from tension specimen tests is 54 ksi, they are $0.4 \sigma_{ys}$ and $0.5 \sigma_{ys}$, respectively. The compressive residual stress is approximately 13 ksi in the mid-portion of the flange and 4 ksi in the mid-portion of the web, which correspond to $0.2 \sigma_{ys}$ and $0.08 \sigma_{ys}$, respectively.

5. SUMMARY

This report describes the results of residual stress measurements in two welded H-shapes manufactured from flame-cut plates of A572 (Grade 50) steel as well in their component flame-cut plates. This is one phase of an overall general investigation into the strength and behavior of columns welded from flame-cut plates.

The conclusions deduced from these measurements are the following:

1. Very high tensile residual stresses exist in the regions close to the flange tips, directly as a result of the flame-cutting.
2. Very high tensile residual stresses also exist in the vicinity of the web-to-flange junctions, due to welding.
3. Compressive residual stresses are rather uniformly distributed in flanges and in the mid-portion of web. The magnitude of compressive residual stress

is more uniform in the smaller shape (12H79) than in the larger shape (14H202).

4. Residual stress distribution in the cross section is constant along the length of the steel members.
5. Comparing the residual stresses in A572 (50) steel with A36 steel, the yield stress has almost no effect on the magnitude and on the distribution of residual stress.
6. The major factor that governs the residual stress is the geometry of the cross section.
7. Comparing the two shapes of A572 (50) steel, the magnitude of residual stress, both in tension and in compression, is greater in the smaller shape (12H79) than in the larger shape (14H202).

6. NOMENCLATURE

\bar{A}_i	Average readings of the gage length i after sectioning.
$\overline{\text{Ref.}\bar{A}_i}$	Average of reference bar readings for the strip i after sectioning.
\bar{B}_i	Average readings of the gage length i before sectioning.
$\overline{\text{Ref.}\bar{B}_i}$	Average of reference bar readings for the strip i before sectioning.
E	Modulus of elasticity.
E_{st}	Strain-hardening modulus.
FC	Flame-cut.
H	Welded wide-flange shape.
L	Gage length.
WF	Rolled wide-flange shape.
ϵ_{st}	Strain at the onset of strain-hardening.
σ_{ri}	Residual stress of the strip i (positive for tensile and negative for compressive residual stress).
σ_u	Ultimate tensile stress.
σ_{ys}	Static yield stress.
kips	One thousand pounds.
ksi	One thousand pounds per square inch.

7. ACKNOWLEDGEMENTS

The investigation was conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania, and was sponsored by the American Iron and Steel Institute. Lynn S. Beedle is the Director of the Laboratory and David A. VanHorn is the Chairman of the Civil Engineering Department.

The technical guidance made by the members of Task Group 1 of the Column Research Council under the chairmanship of John A. Gilligan is gratefully appreciated.

The authors owe special thanks to their research colleagues at Fritz Engineering Laboratory for their assistance for the research, especially to Ching-Kuo Yu and Jacques Brozzetti.

Appreciation is also due Kenneth R. Harpel, lab foreman, and his staff for their cooperation in conducting the tests.

The authors wish to express their sincere appreciation to Richard N. Sopko for his fine work on the photographs, to John M. Gera and his staff for all drawings, and to Miss Joanne Mies for her typewriting of the entire manuscript.

8. TABLES AND FIGURES

Table 1 NUMBER OF SPECIMENS

Test	Member	12H79	14H202
Tension Test	Shape	12-Flange	3-Flange
		3-Web	1-Web
	Loose Plate	0	6-Flange Plate 2-Web Plate
Residual Stress Measure- ment	Shape	3	2
	Loose Plate	0	2-Flange Plate 1-Web Plate

Table 2 Tension Specimen Test Results

Shape or Plate	Specimen No.	Static Yield Stress (ksi)	Modulus of Elasticity (10^3 ksi)	Ultimate Stress (ksi)	Strain* at Strain-Hardening (%)	Strain-* Hardening Modulus (ksi)	Elongation in 8 in. Gage Length (%)	Reduction of Area (%)
Shape 12H79 (Flange)	3A1	55.3	29.9	85.6	—	—	24.8	45.0
	3A2	57.2	29.7	85.8	1.10	748	25.6	48.9
	3A4	54.0	31.2	82.8	1.05	698	26.5	50.3
	3A5	54.8	28.6	82.6	1.14	710	25.8	52.4
	3B1	55.5	28.7	84.9	1.07	691	26.0	47.9
	3B2	56.7	20.4	85.0	1.58	411**	25.3	47.9
	3B4	54.2	29.8	84.4	1.00	676	25.3	47.7
	3B5	54.9	29.5	82.6	1.12	685	26.4	51.3
	3C1	56.7	30.2	86.1	0.80	712	23.9	46.6
	3C2	56.7	28.6	85.6	1.01	728	24.5	46.8
	3C4	57.1	28.8	86.9	0.86	777	22.3	44.9
	3C5	57.3	28.4	87.2	0.90	758	20.5	44.8
Flange Average		55.9	—	85.0	1.06	719	24.7	47.9
Shape 12H79 (Web)	3A3	56.5	30.8	74.6	1.83	436	22.8	46.1
	3B3	54.6	18.2	78.2	—	—	27.1	48.1
	3C3	55.6	28.0	73.2	1.97	506	25.8	48.8
Web Average		55.6	—	75.4	1.90	471	25.2	47.7
Average †		55.8	—	82.7	1.25	662	24.8	47.9
Shape 14H202 (Web)	4B1	55.3	22.3	86.5	—	823	26.5	56.5
	4B2	55.1	28.5	86.6	0.86	859	27.0	56.8
	4B3	55.0	27.0	86.0	—	840	23.8	40.7
Flange Loose Plate	4E1	51.4	29.3	83.6	0.63	771	27.2	58.8
	4E2	52.4	29.3	83.7	0.67	836	26.7	58.7
	4E3	52.6	28.2	84.7	0.63	839	26.6	56.8
	4F1	53.9	29.7	84.4	0.50	836	27.8	58.1
	4F2	—	26.4	85.0	0.53	808	26.9	57.0
	4F3	54.5	30.2	85.1	0.44	849	26.5	56.6
Flange Average		53.8	—	85.1	0.61	829	26.6	55.6
14H202 (Web)	4B4	54.0	—	80.8	1.04	723	26.9	56.6
Web Loose Plate	4D1	54.7	28.8	84.5	0.76	796	22.6	49.3
	4D2	55.3	29.5	84.2	0.72	714	23.6	50.1
Web Average		54.7	—	83.2	0.84	744	24.4	52.0
Average †		54.0	—	84.7	0.65	811	26.1	54.8

* Estimated from load-elongation diagrams drawn by an automatic recorder.

** Omitted when averaging

† Weighted average

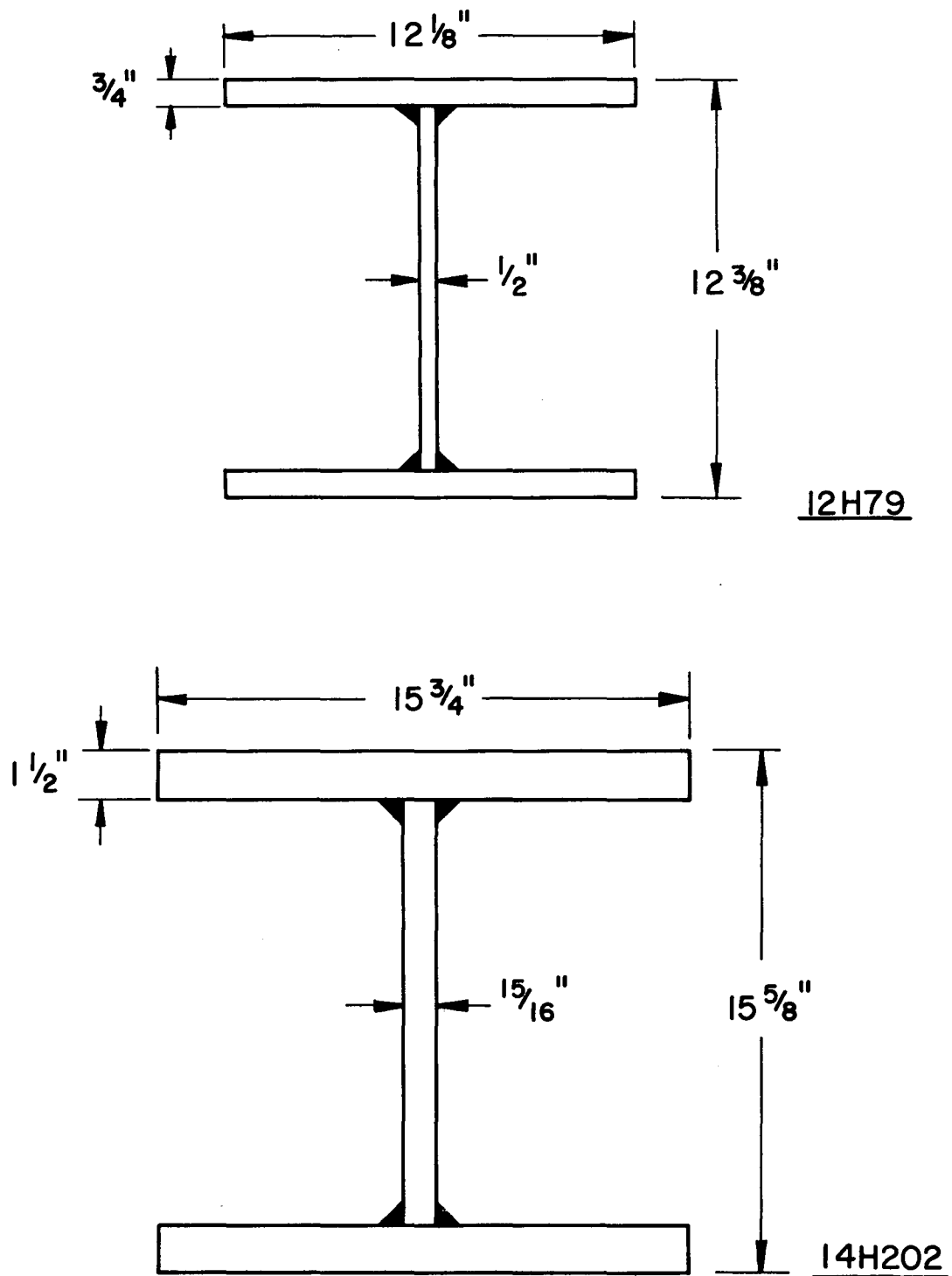
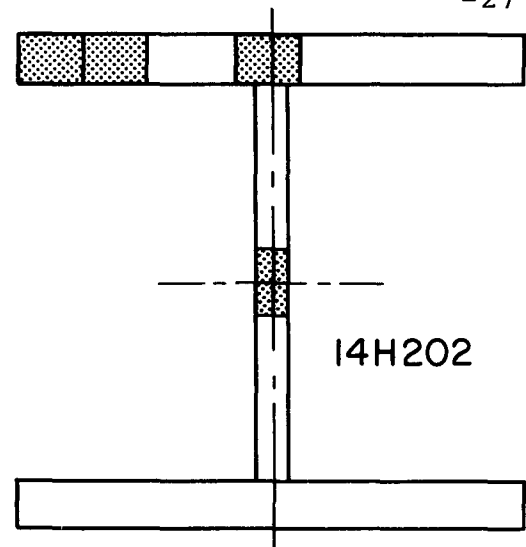
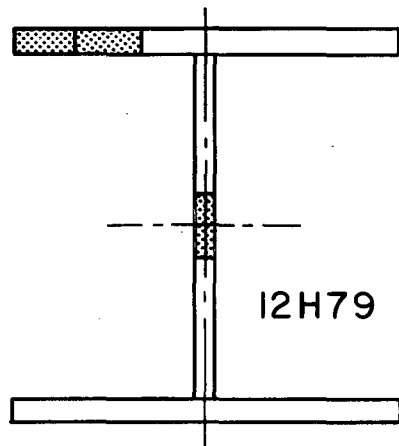


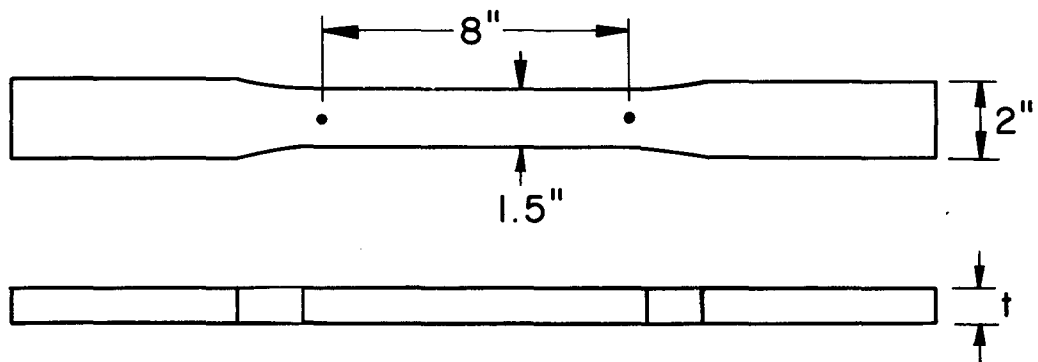
Fig. 1 Dimensions of the Shapes Studied



Flange Plate



Web Plate



	I2H79		I4H202	
	Flange	Web	Flange	Web
t	3/4"	1/2"	1 1/2"	15/16"

Fig. 2 Location of Tension Test Specimens in Cross Sections

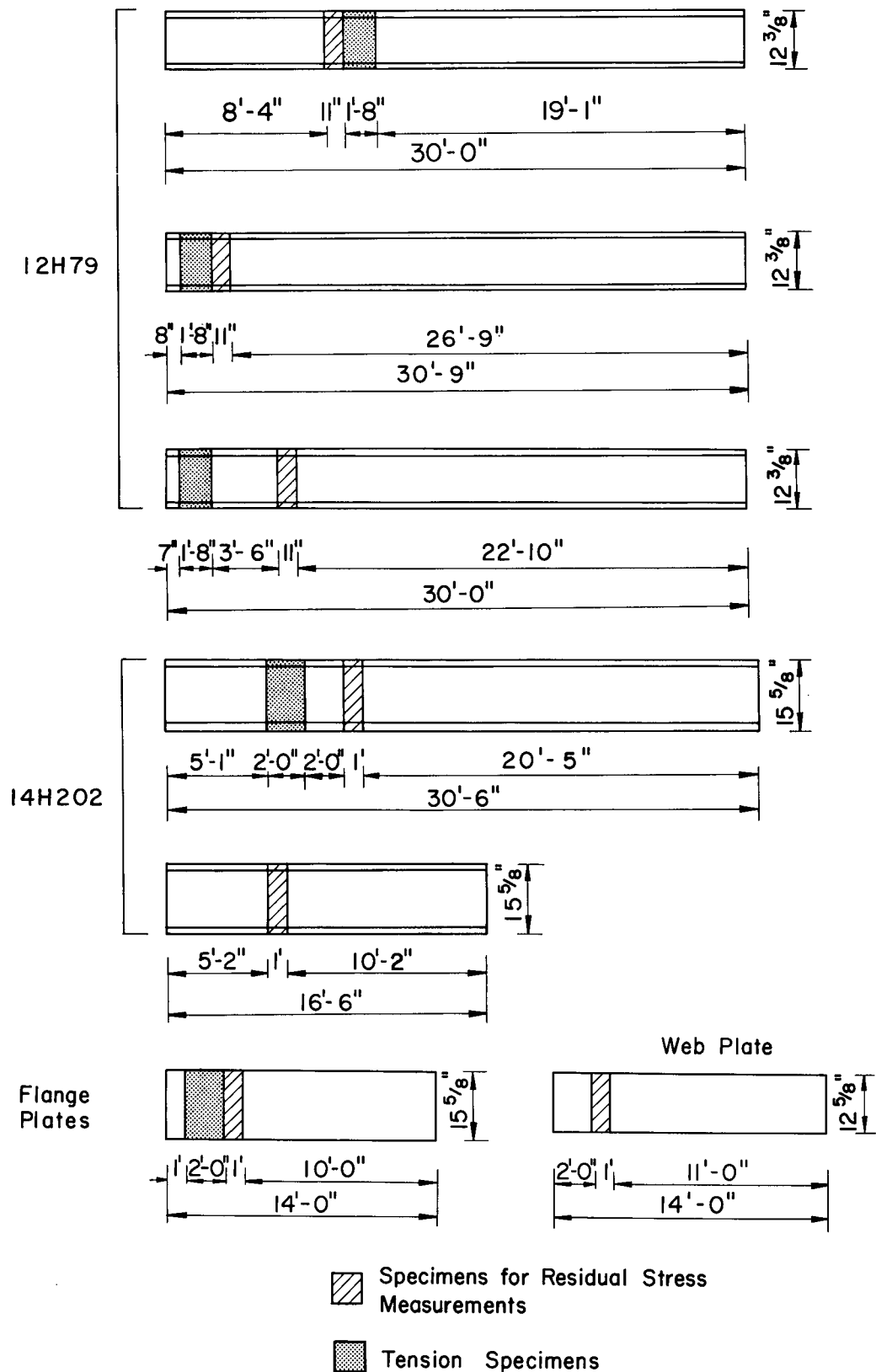


Fig. 3 Layout of Test Specimens



Fig. 4 Whittemore Strain Gage

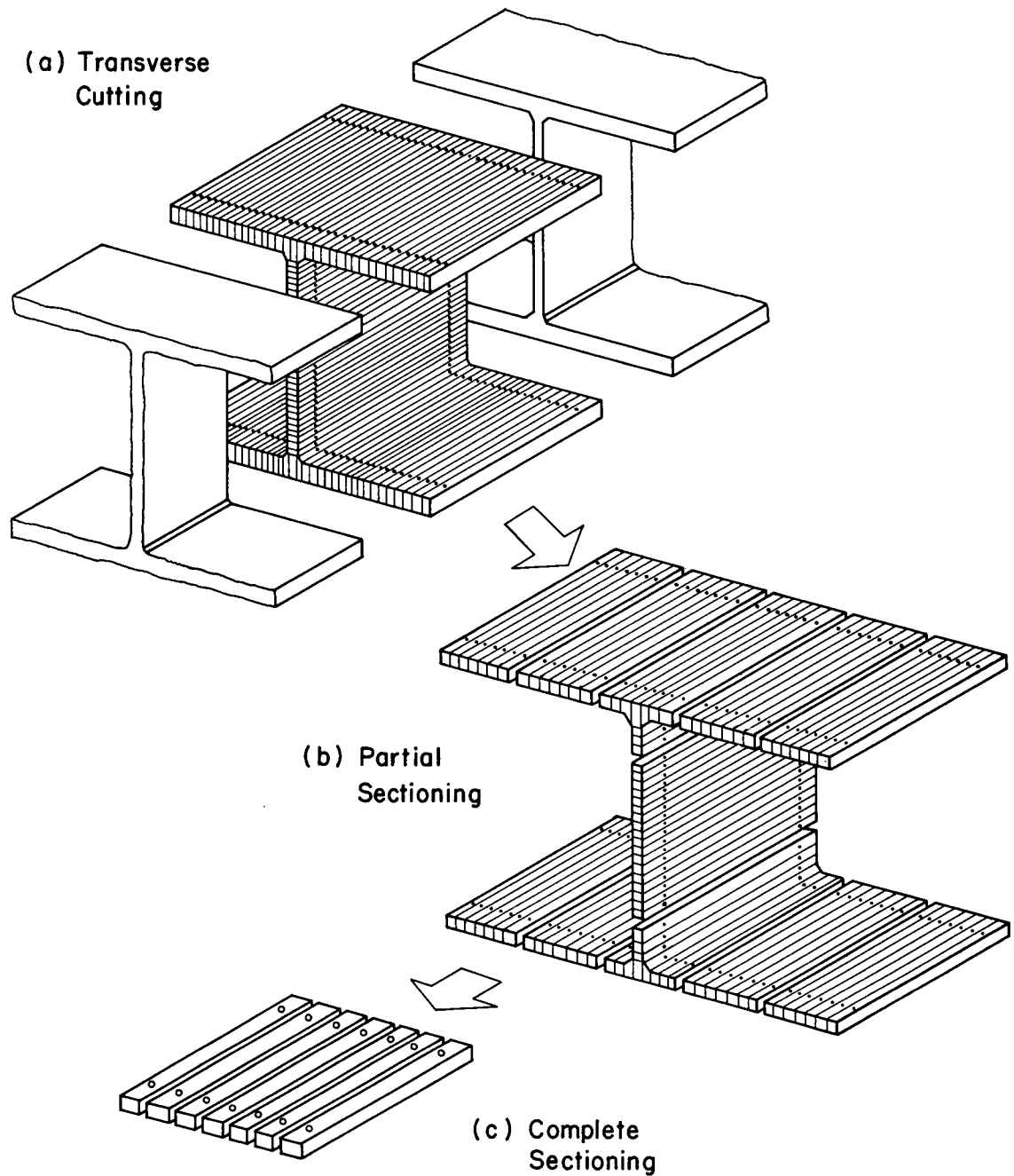


Fig. 5 Sectioning Steps

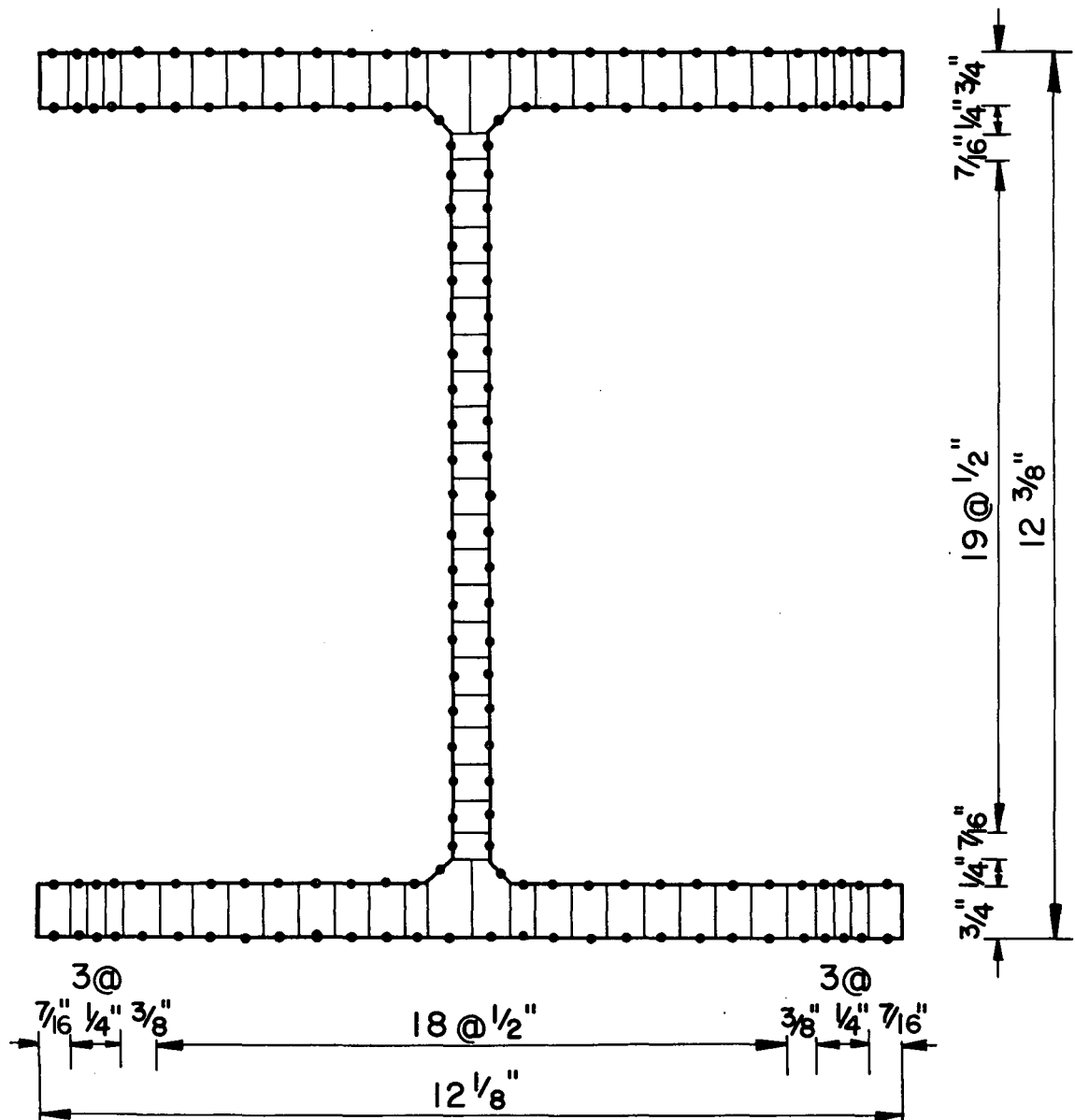


Fig. 6 Sectioning Details for 12H79 Shapes

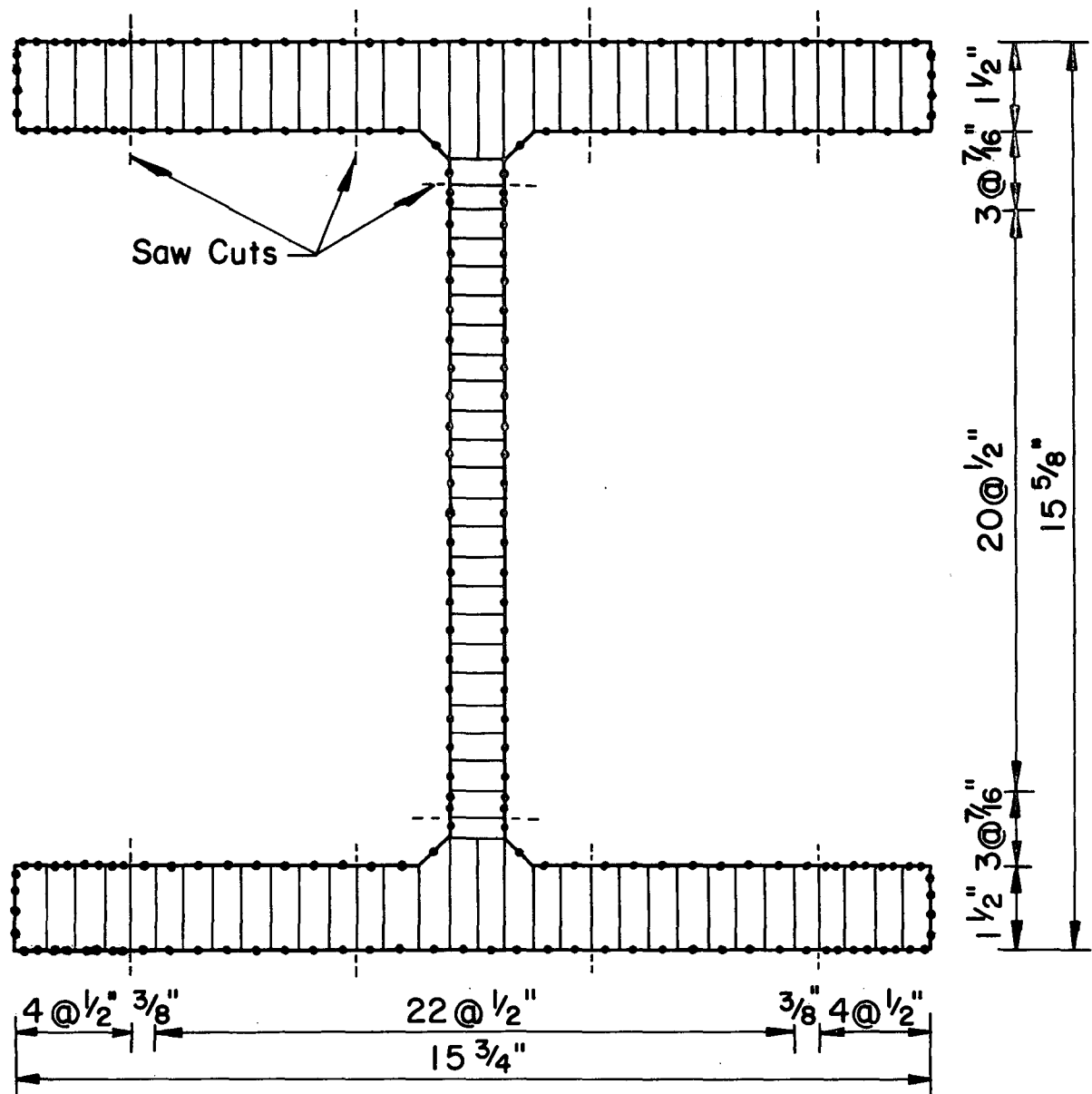
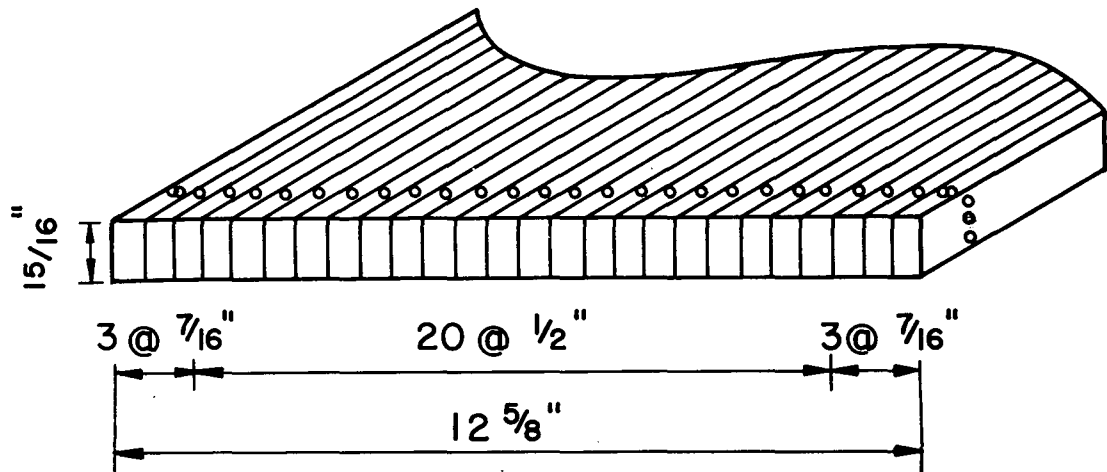
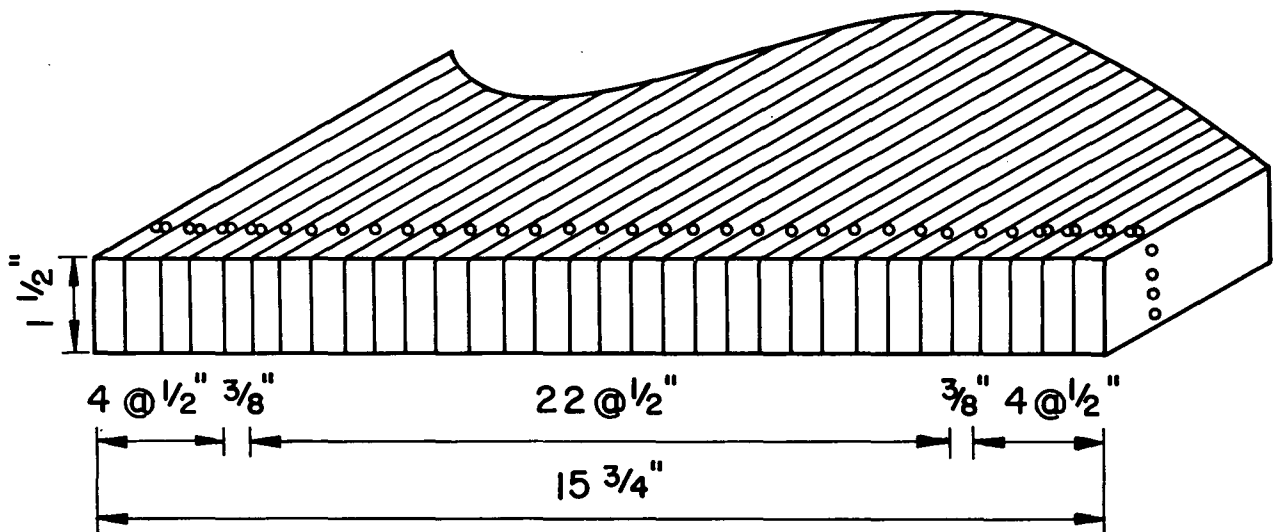


Fig. 7 Sectioning Details for 14H202 Shapes



(a) Web Plate (4D)



(b) Flange Plates (4E and 4F)

Fig. 8 Sectioning Details for Plates

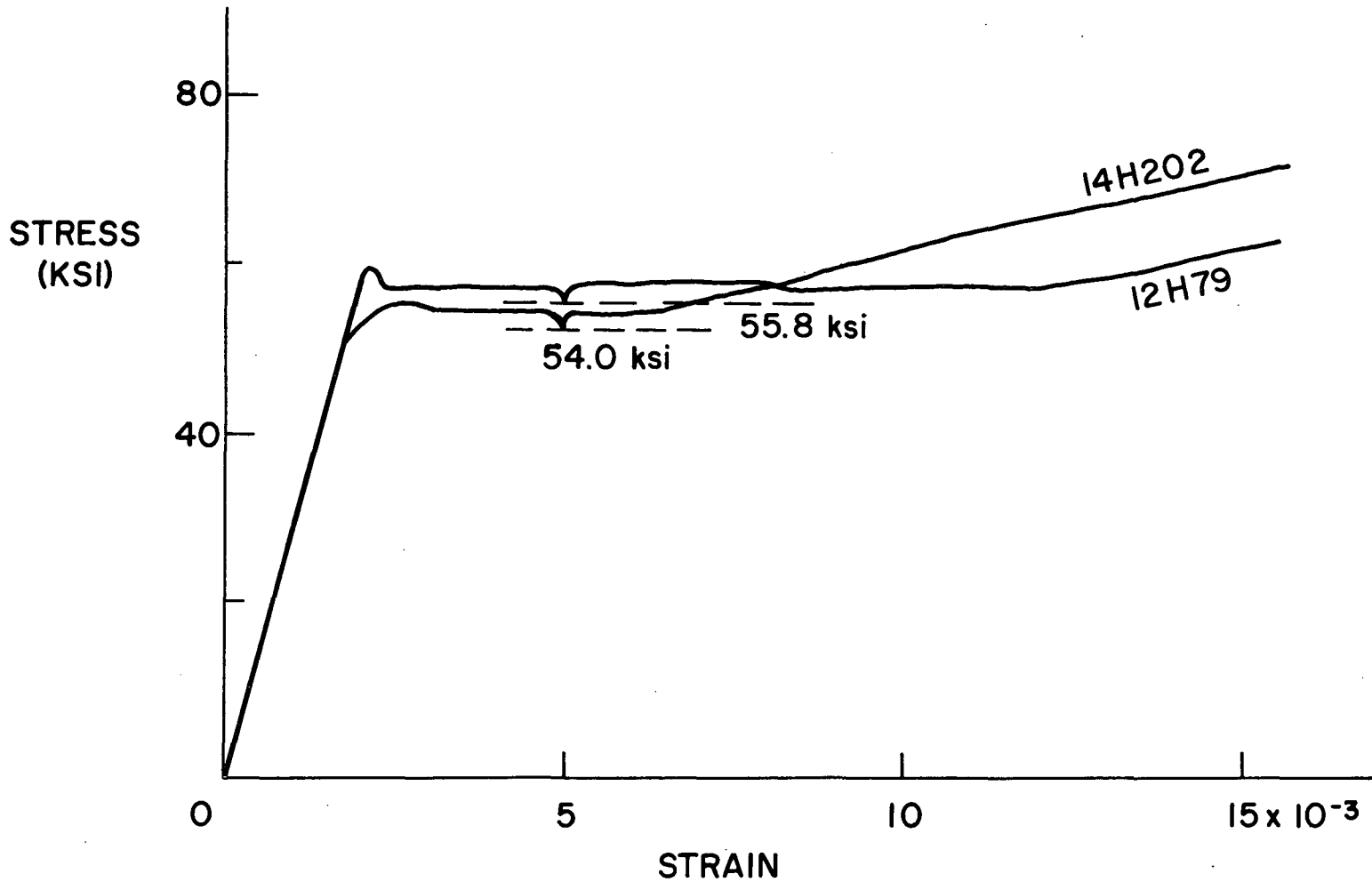
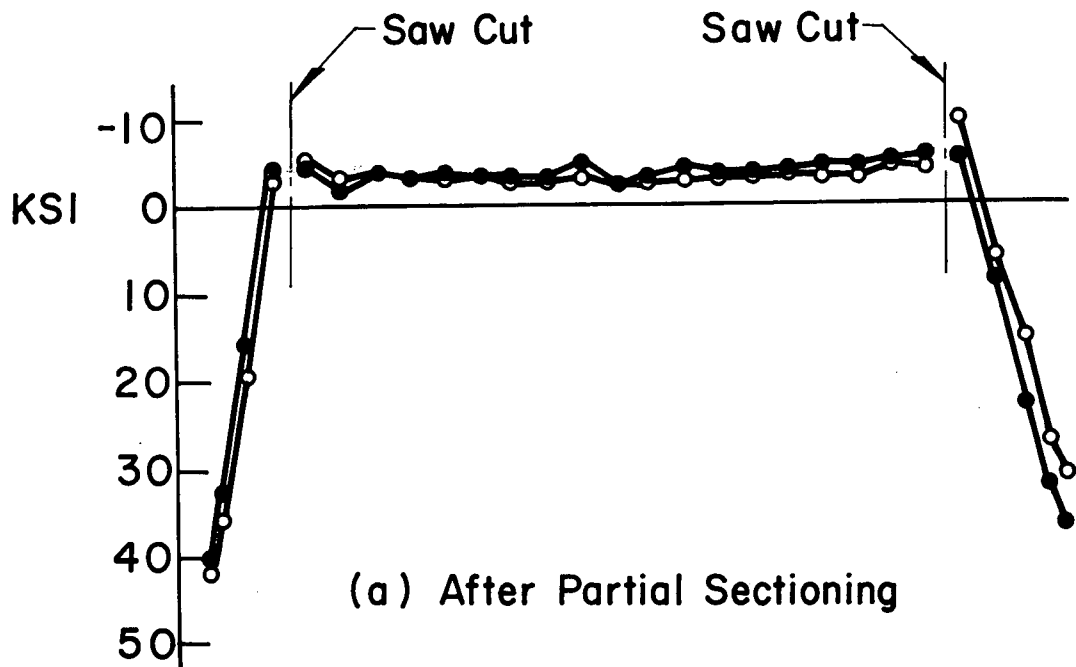
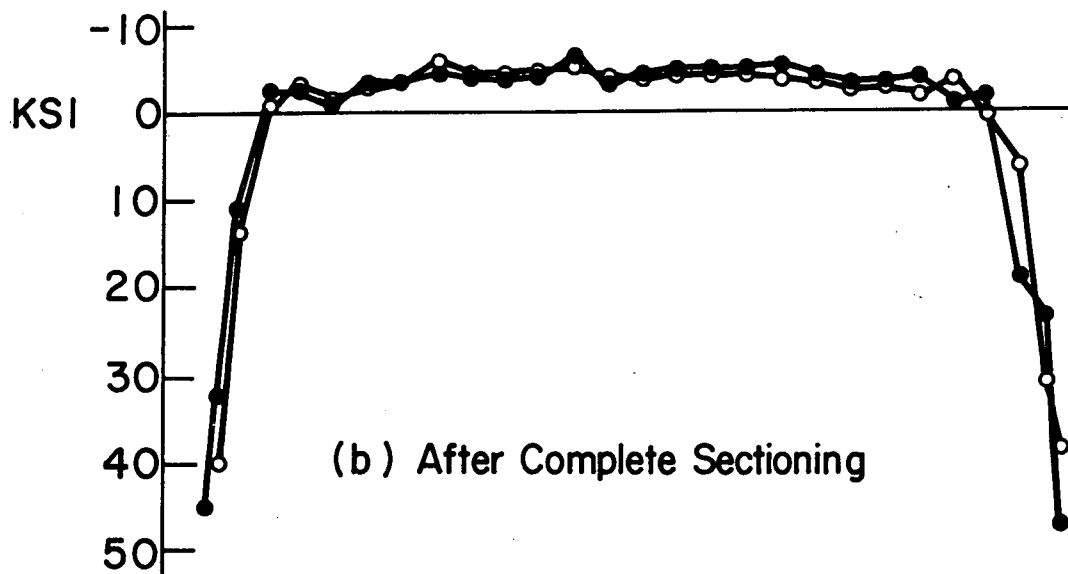


Fig. 9 Average Stress-Strain Curves Obtained from
Tension Specimen Tests -- A572(Grade 50) Steel



(a) After Partial Sectioning



(b) After Complete Sectioning

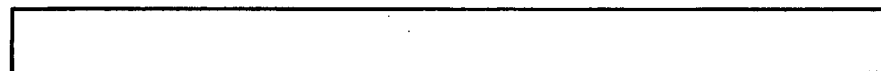
Plate $12 \frac{5}{8}'' \times 1 \frac{5}{16}''$ (FC), A572 (50)

Fig. 10 Residual Stress Distribution in Web Plate: 4D

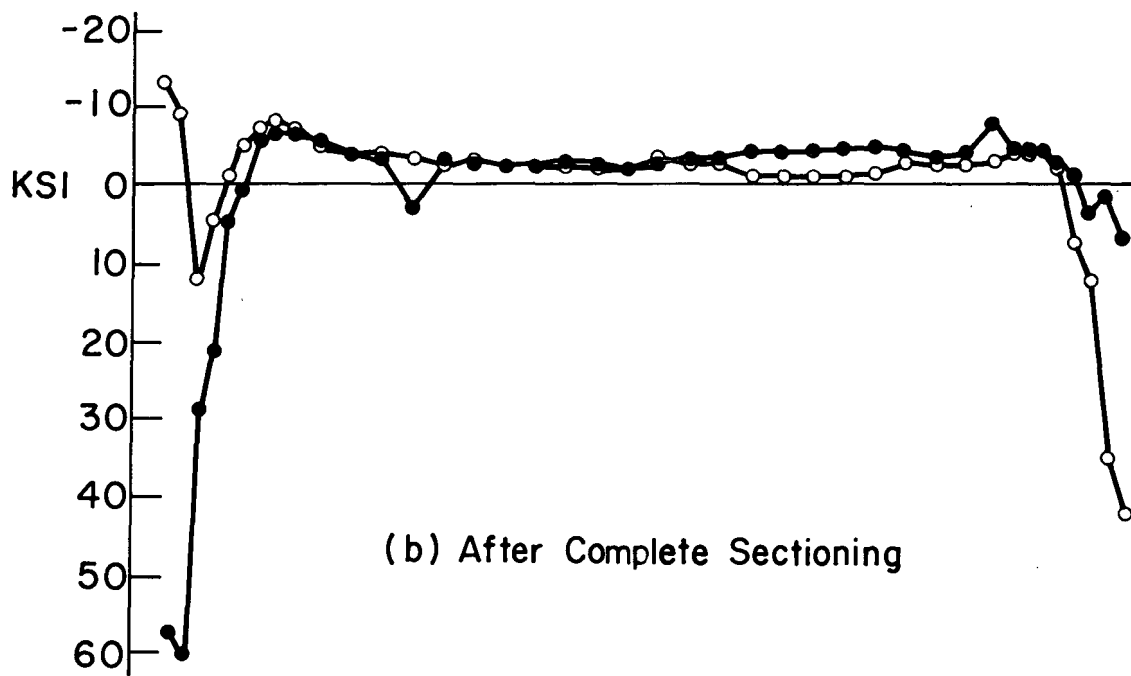
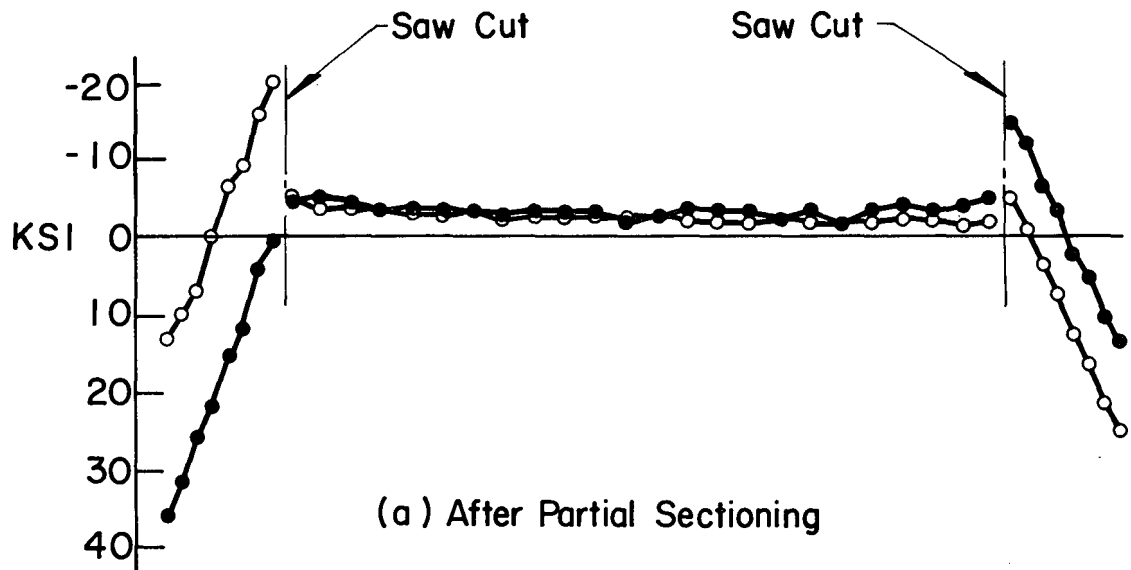


Plate $15 \frac{3}{4}'' \times 1 \frac{1}{2}''$ (FC), A572 (50)

Fig. 11 Residual Stress Distribution in Flange Plate: 4E

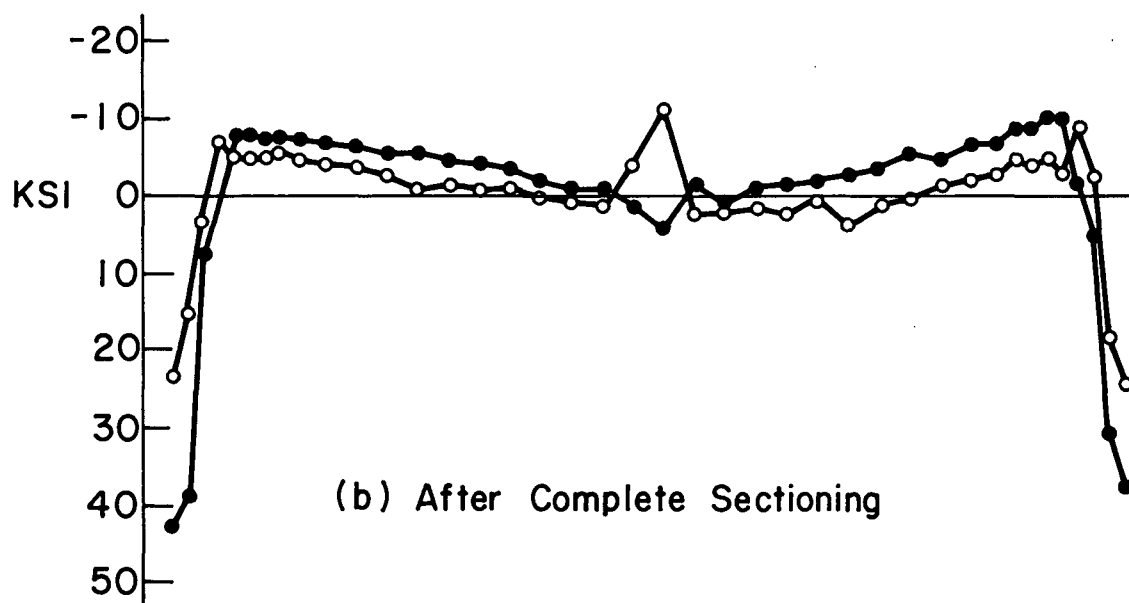
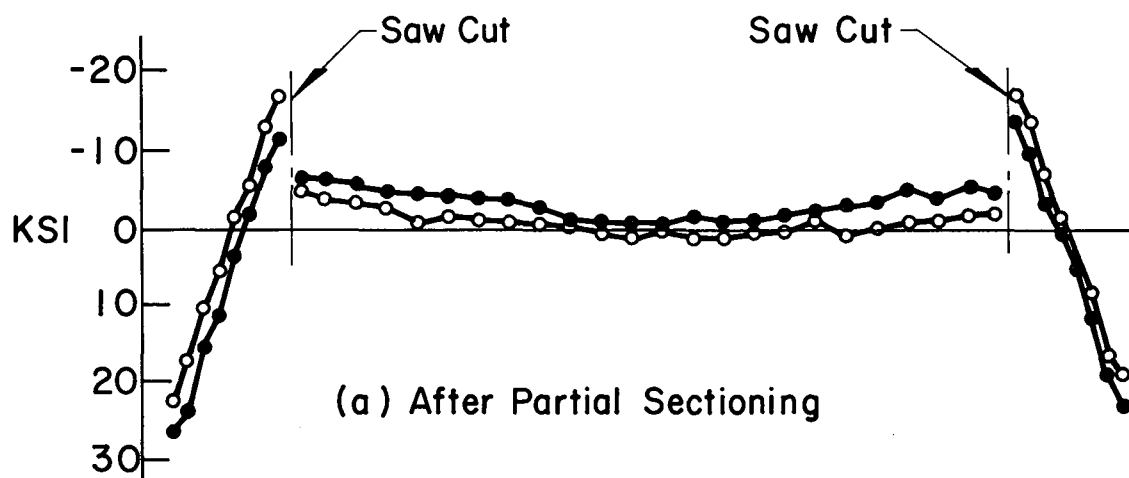


Plate $15\frac{3}{4}'' \times 1\frac{1}{2}''$ (FC), A572 (50)

Fig. 12 Residual Stress Distribution in Flange Plate: 4F

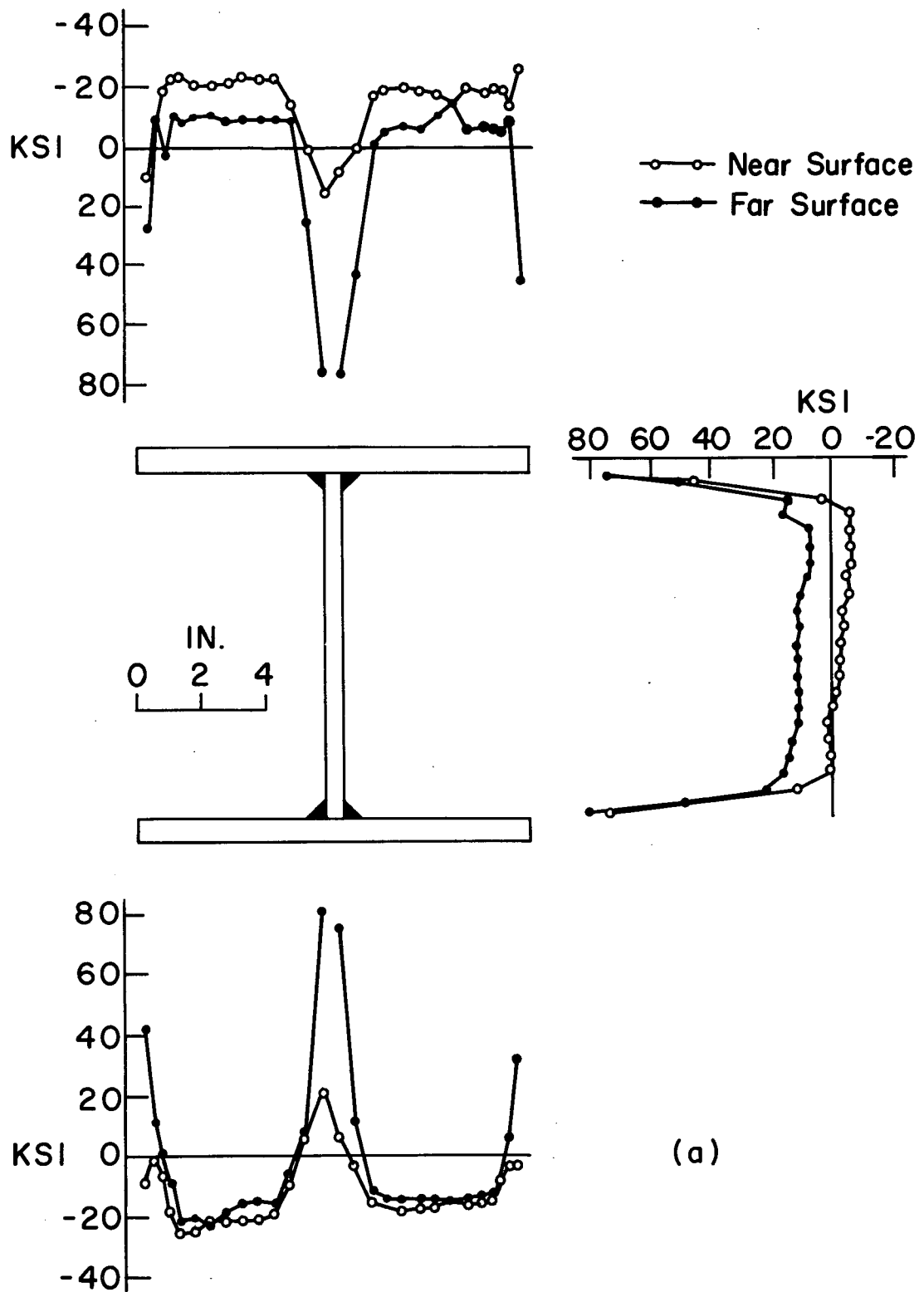


Fig. 13 Residual Stress Distribution in 12H79 (FC) Shape, A572(50) Steel

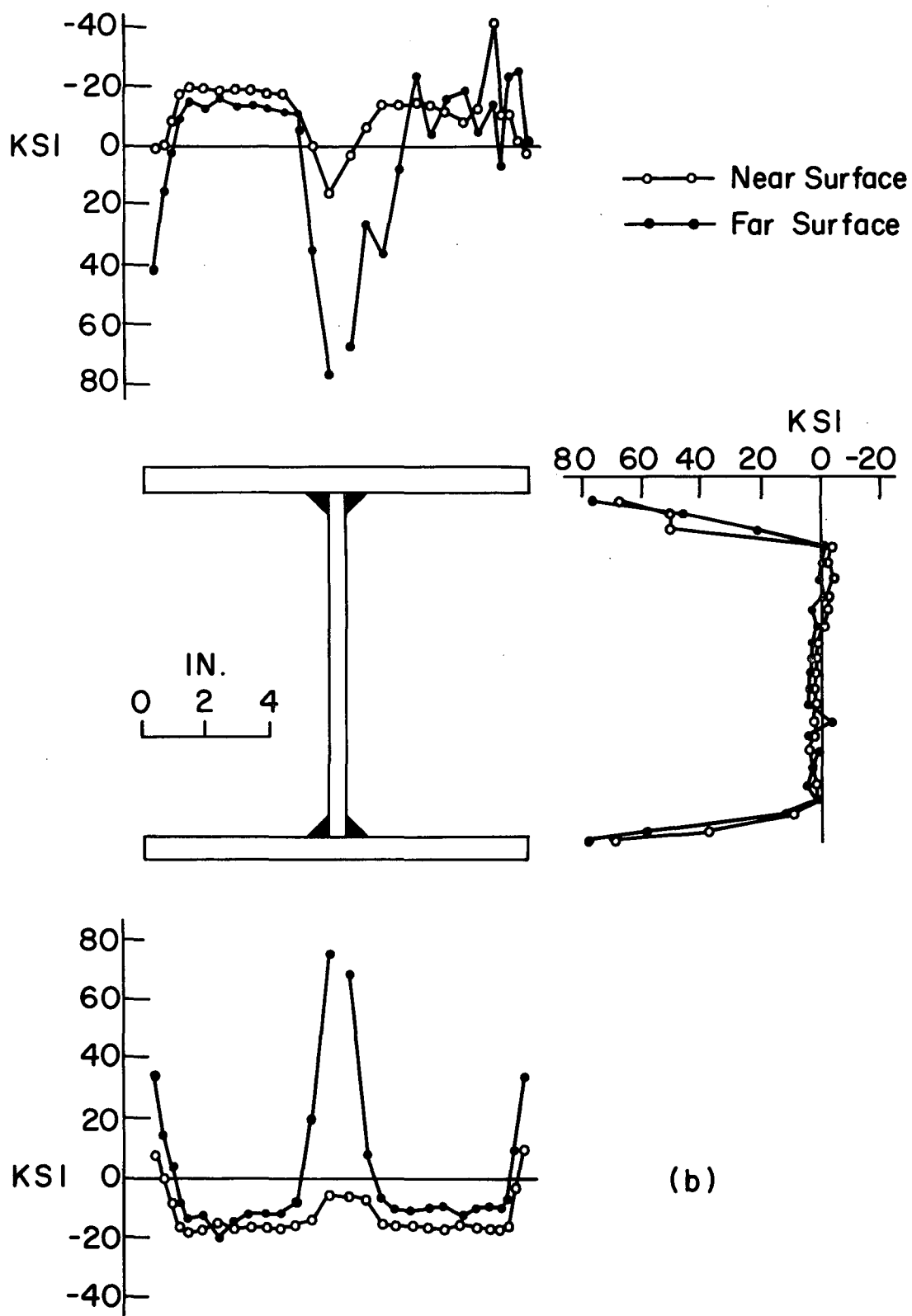


Fig. 13 Residual Stress Distribution in 12H79 (FC) Shape, A572 (50) Steel (Continued)

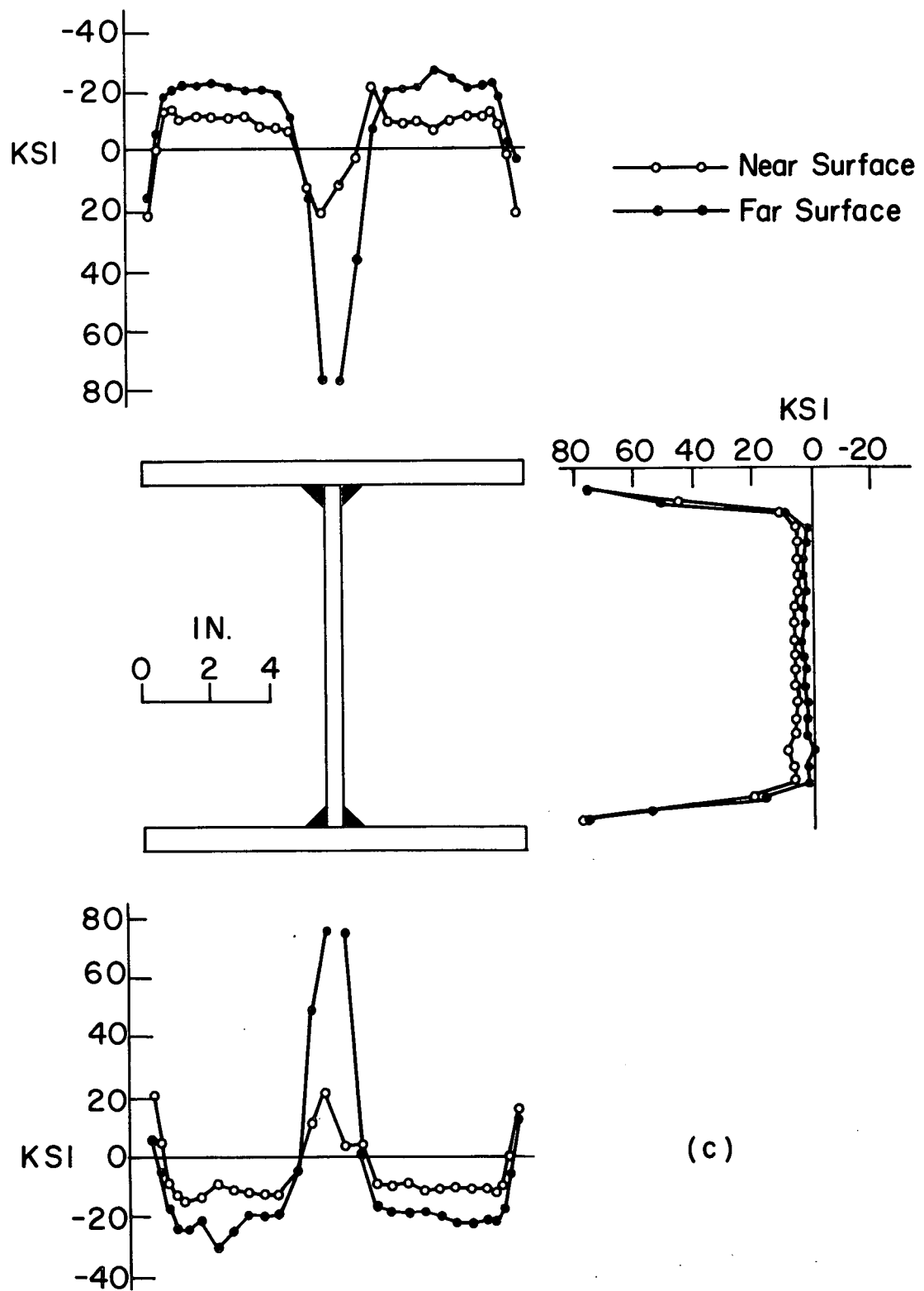


Fig. 13 Residual Stress Distribution in 12H79 (FC) Shape, A572 (50) Steel (Continued)

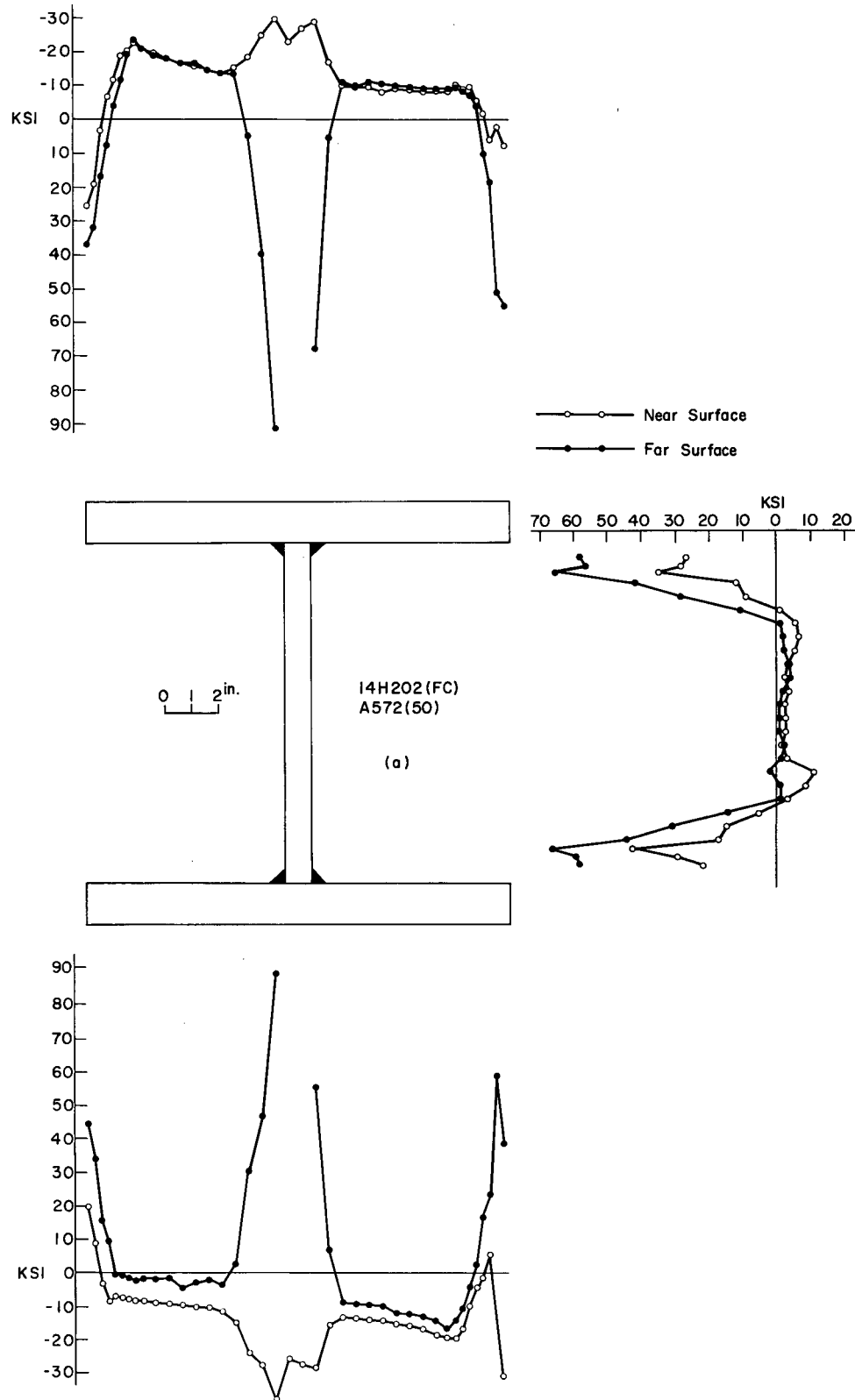


Fig. 14 Residual Stress Distribution in 14H202 (FC) Shape, A572(50) Steel

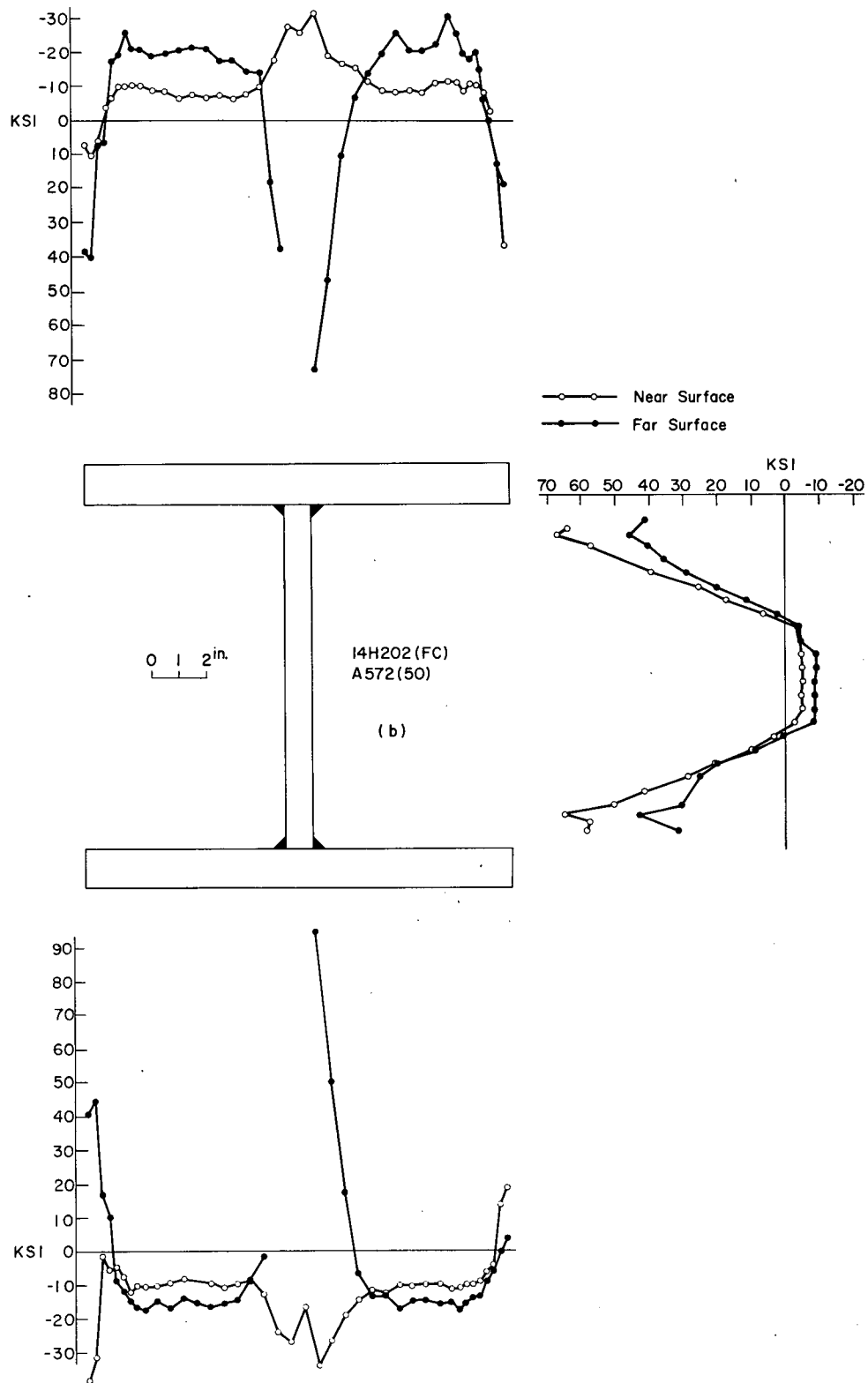


Fig. 14 Residual Stress Distribution in 14H202 (FC) Shape, A572 (50) Steel (Continued)

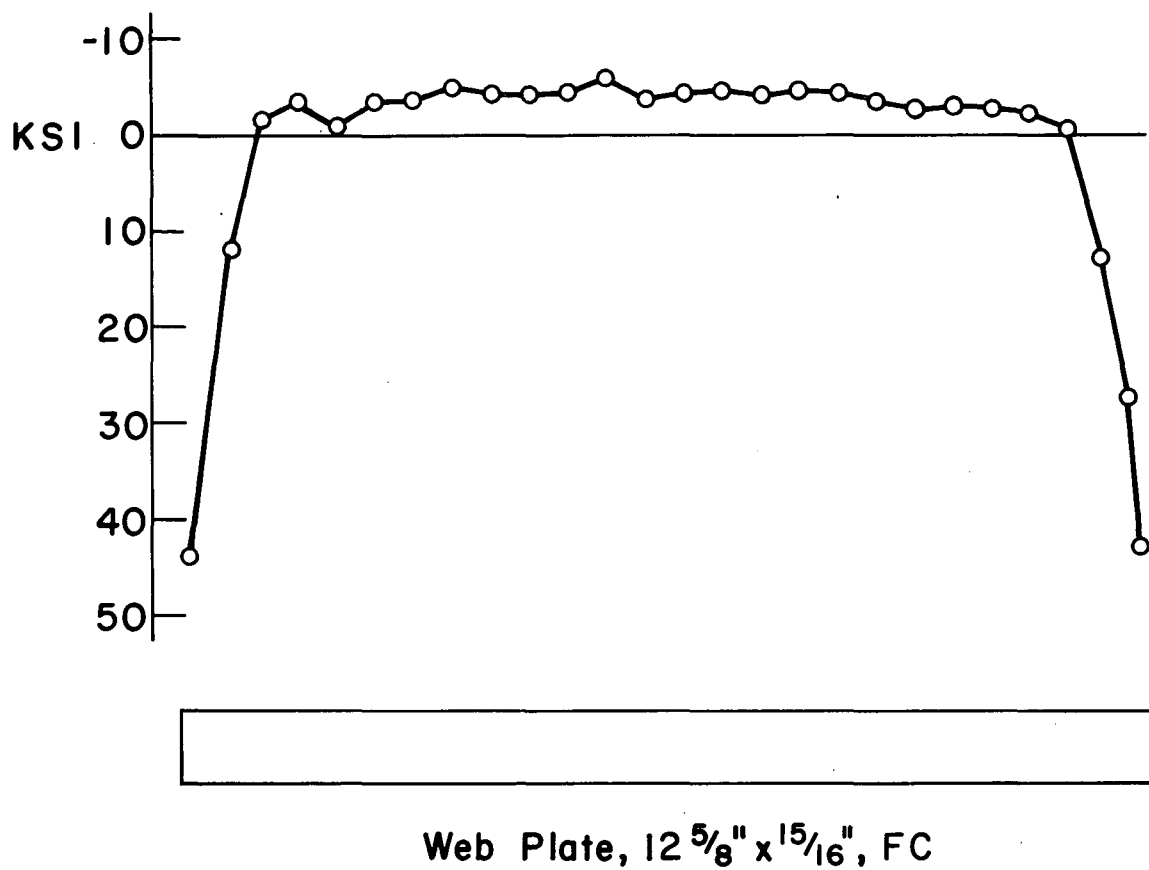


Fig. 15 Average Residual Stress Distribution in Web Plate (4D), A572(50) Steel

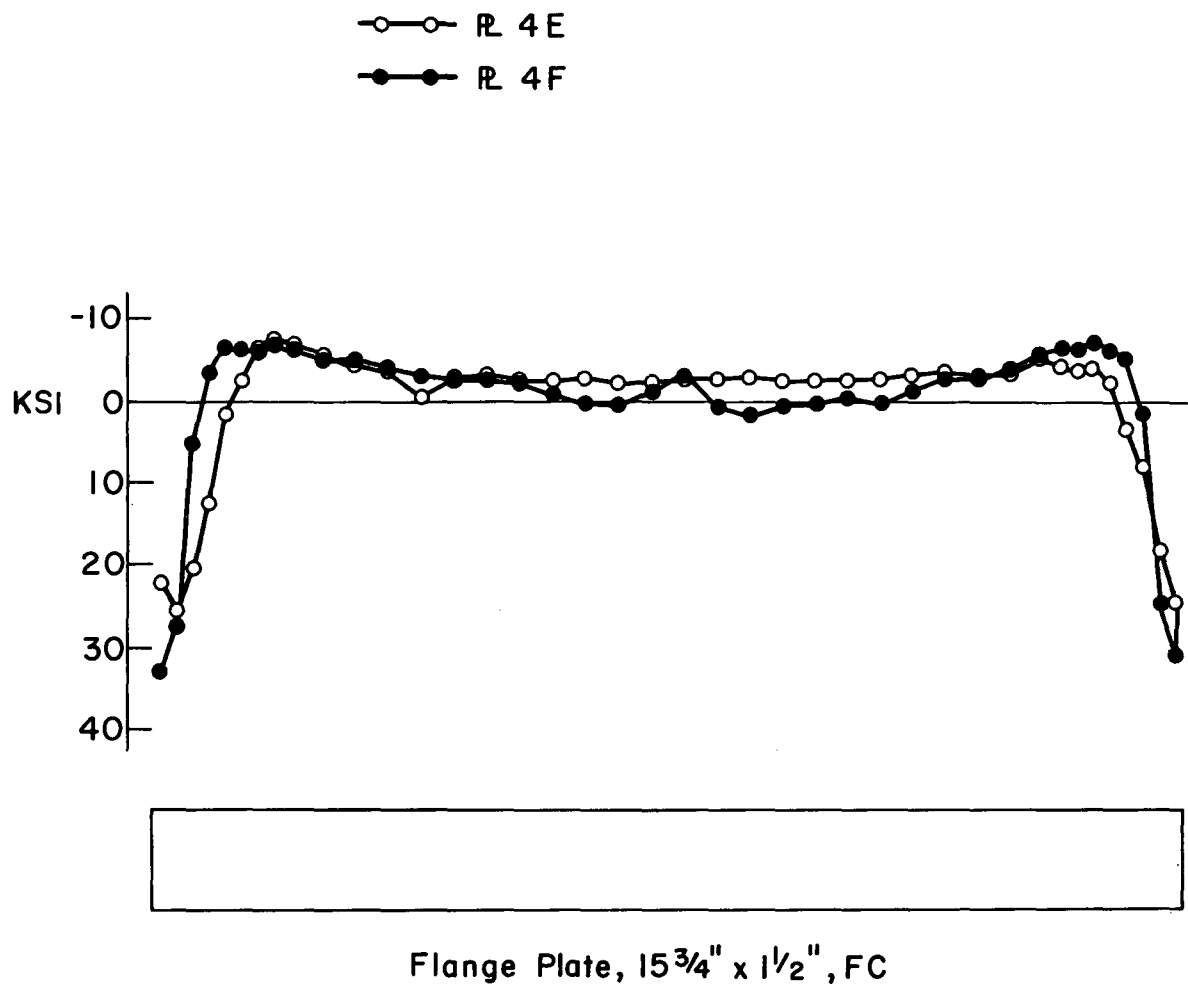


Fig. 16 Average Residual Stress Distribution in
Flange Plates (4E and 4F), A572(50) Steel

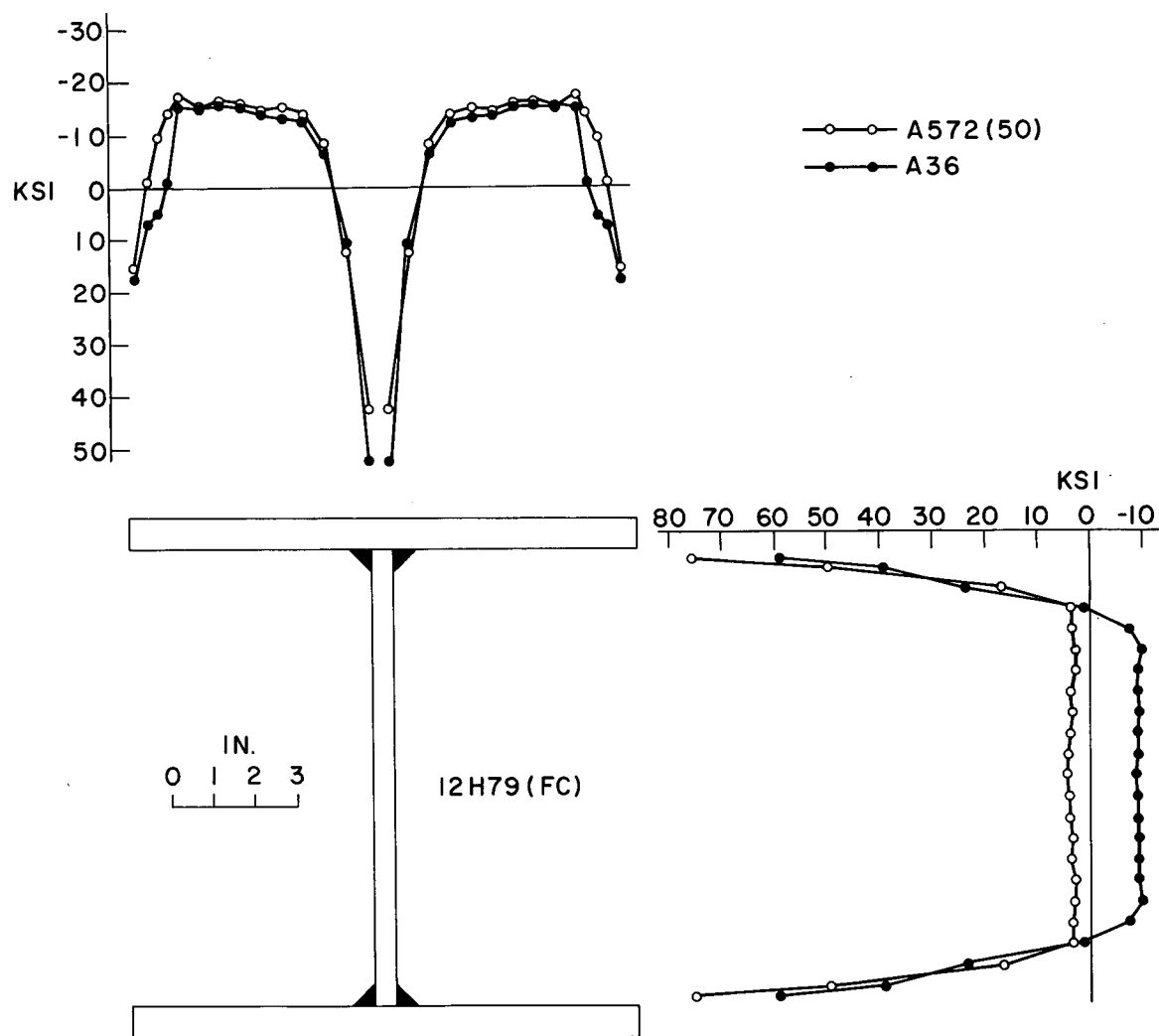


Fig. 17 Average Residual Stress Distribution in 12H79 (FC) Shape

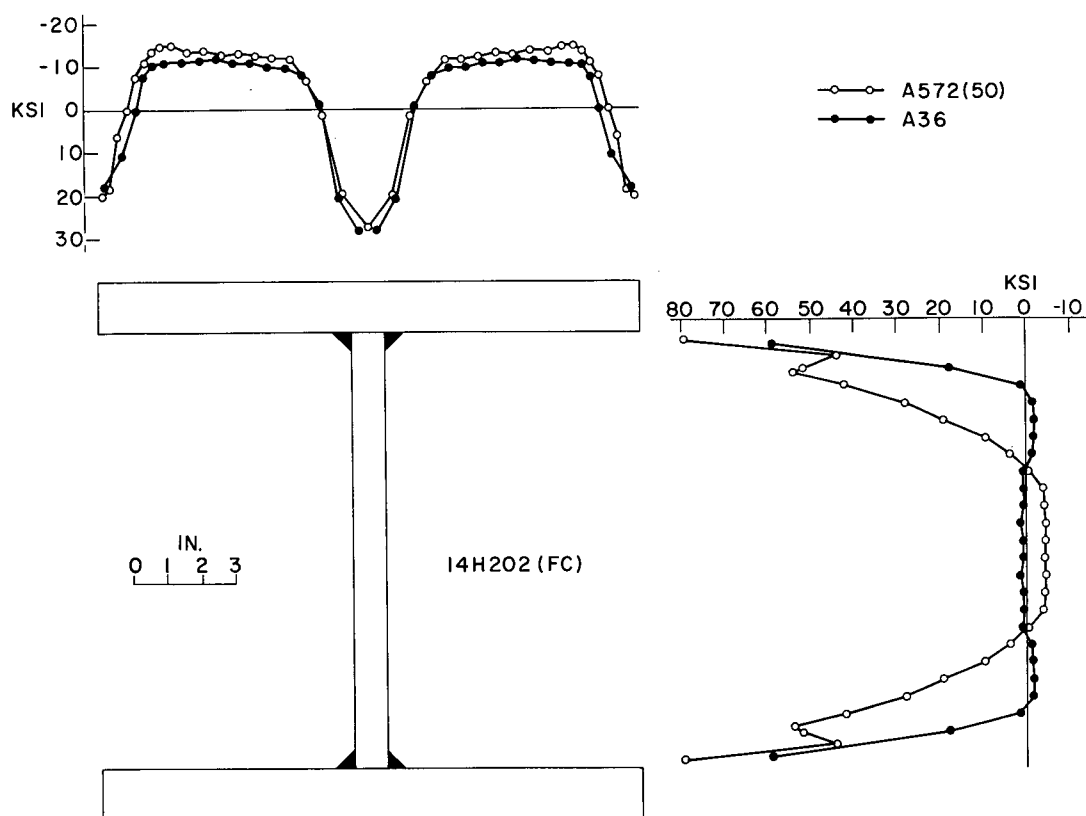


Fig. 18 Average Residual Stress Distribution in 14H202 (FC) Shape

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